THE CHARACTERISTIC OF FREQUENCY RESPONSE ON WINDING FAULTS AND CONFIGURATIONS OF TRANSFORMER

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A thesis submitted in
fulfillment of the requirements for the award of the
Degree of Master of Electrical Engineering

Faculty of Electrical and Electronic Engineering
Universiti Tun Hussein Onn Malaysia

AUGUST 2019

Specially thanks to:

My lovely family

Md. Yasid bin Mahusin, Norini bt Ghani, Nurul Farhana, Mohd Azrol,
Nurul Fatihah, Nurul Ayuni,
Mohd Asyraf

Friends

All my friends that gives sincere support

Supervisor

Dr. Mohd Fairouz bin Mohd Yousof

Thank you all for your love, support, encouragement, and prayers

ACKNOWLEDGEMENT

All praise is due to Allah, the Most Gracious and the Most Merciful. I am truly grateful to many people for their support towards my study and finally completing this research project.

First, I would wish to state my deepest and earnest gratitude to my project supervisor, Dr. Mohd Fairouz bin Mohd Yousof. His extensive knowledge and his logical way of thinking have been a capital value for me. His understanding, encouraging and personal guidance provide a good basic for this present thesis.

My special gratitude to my parents, Md. Yasid bin Mahusin and Norini bt Ghani, brother and sisters for their endless loving and financial support. Thank you for the guidance and motivation throughout my studies all the time.

Also, I would like to thank my friends for their friendship, ideas and support. I wish to extend my warmest thank to all those who have assisted me with my work who have contributed directly or indirectly towards this research.

Last but not least, I really appreciate to have this opportunity to finish this research project. This task has taught a great deal of lesson and knowledge which would be valuable to me in the time to come.

Thank you.

ABSTRACT

This research presents a study on the monitoring of several winding configurations of power transformers using Frequency Response Analysis (FRA). The frequency response provides indications of any mechanical and electrical changes in the transformer's active parts. Three units of three-phase transformers were tested with the aim to investigate their FRA responses due three case studies. They are due to vector group, three types of faulty winding and also the effect of coupling in the three-phase core-typed transformers. The tests were repeated to Dyn11 360VA, 100kVA and 500kVA core-typed transformers to carry out the desired condition scenario of the FRA responses. Transformer Turn Ratio (TTR) and winding resistance test are performed to establish the present condition of the transformers winding. The TTR test is conducted to determine the turn ratio of high voltage (HV) to the low voltage (LV) windings at no load condition. Meanwhile, winding resistance test is performed to check for gross difference between the windings. From these test results, it is found that the windings are in good condition. The first case is to investigate the characteristics of the FRA response due to different vector groups. It is found that it gives subtle to the response and mainly altering the medium frequency region. The second case study is the investigations of the effect of three types of faulty winding in the FRA response. They are performed by physically simulate the faults to the transformers. The faults are inter-turn short circuit (SC) fault, local overheating and radial deformation. The results show that the SC causes the starting magnitude to increase and the resonance at the low frequency region to shift towards higher frequencies. Meanwhile, during local overheating fault, the winding carries out additional resistance at the winding. It is found that it causes the alteration of the response at the very low frequency region. Lastly, the study found that radial deformation causes the responses to change in the mid-frequency region. The third case study is to investigate the effect of coupling in the three-phase transformers. This is performed by investigating the effect of fault at winding of other phases to the response of measured phase. It is found that faulty occurred in winding of other phases could actually affect the response of measured winding. The location of the fault determines how severe it is affecting the response. The findings from this research could be helpful in enriching the knowledge to evaluate the FRA response.

ABSTRAK

Penyelidikan ini membentangkan kajian mengenai pemantauan beberapa konfigurasi penggulungan pengubah dengan menggunakan Analisis Frekuensi Kekerapan (FRA). Tindak balas frekuensi memberikan petunjuk tentang sebarang perubahan mekanikal dan elektrik di bahagian aktif pengubah. Tiga unit transformer tiga fasa telah diuji dengan tujuan untuk menyiasat tindak balas FRA terhadap tiga kajian kes. Ianya adalah kumpulan vektor, tiga jenis penggulungan yang rosak dan juga kesan gandingan dalam pengubah tiga fasa jenis teras. Ujian ini diulang kepada 360VA, 100kVA dan 500kVA, Dyn11, transformer jenis teras untuk mendapatkan senario keadaan yang dikehendaki dari respon FRA. Ujian *Transformer Turn Ratio (TTR)* dan *winding resistance* telah dijalankan untuk menunjukkan keadaan penggulungan pada masa sekarang. Ujian *TTR* dijalankan untuk menetukan ratio penggulungan pada voltan tinggi (HV) kepada voltan rendah (LV) semasa tiada beban. Manakala ujian *winding resistance* dijalankan untuk memeriksa perbezaan diantara penggulungan. Daripada keputusan ujian, didapati keadaan pengulungan adalah baik. Kes pertama adalah untuk mengkaji ciri-ciri tindak balas FRA disebabkan oleh kumpulan vektor yang berbeza. Didapati bahawa ia memberikan kesan kepada respon, terutamanya mengubah rantau frekuensi sederhana. Kajian kes kedua adalah penyiasatan kesan tiga jenis penggulungan rosak dalam tindak balas FRA. Ianya dilakukan dengan mensimulasikan kerosakan secara fizikal kepada transformer. Kerosakan tersebut adalah litar pintas (SC), pemanasan setempat dan ubah bentuk radial. Keputusan menunjukkan bahawa SC menyebabkan magnitud permulaan meningkat dan resonan di rantau rendah beralih ke arah frekuensi yang lebih tinggi. Kerosakan pemanasan setempat menyebabkan penggulungan mengalami pertambahan rintangan. Ia didapati menyebabkan perubahan tindak balas di rantau frekuensi yang sangat rendah. Akhir sekali, kajian mendapati bahawa ubah bentuk radial menyebabkan tindak balas berubah di kawasan frekuensi pertengahan. Kajian kes ketiga adalah untuk menyiasat

kesan gandingan transformer tiga fasa. Ini dilakukan dengan menyiasat kesan kerosakan pada penggulungan fasa-fasa lain kepada tindak balas fasa yang diukur. Didapati bahawa kerosakan yang berlaku dalam penggulungan fasa-fasa lain boleh menjejaskan tindak balas penggulungan yang diukur. Lokasi kerosakan menentukan tahap ia memberi kesan kepada tindak balas. Penemuan dari kajian ini boleh membantu dalam memperkayakan pengetahuan untuk menilai tindak balas FRA.

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LIST OF SYMBOLS AND ABBREVIATIONS

AC	–	Alternating current
B	–	Flux density
C	–	Capacitance
C_s-C_{gw}	–	Series-shunt capacitances
$C_{g,w}$	–	Shunt capacitance
C_s	–	Series capacitances
C_g	–	Ground capacitance / Parallel capacity against copper /Core
C_{12}	–	Mutual coupling capacity between HV and LV winding
dB	–	Decibel
F	–	Magnitude of force
I	–	Current intensity
I_f	–	Fault current
ℓ	–	Length of flux path
L	–	length of conductor / Leakage inductance of winding
L_m	–	Magnetizing inductance
L_M	–	Mutual coupling of windings
L_i	–	Winding inductances
L_{12}	–	Mutual coupling inductance HV and LV winding.
N_1, N_2	–	Winding ratio of transformer
R	–	Resistor
R_m	–	Magnetic losses of core
R_1	–	Ohmic resistance of primary winding
Tx	–	Transformer

Zf	–	Fault impedance
Ω	–	Ohm
Φ	–	Flux
CCF	–	Cross correlation factor
CIGRE	–	International Council on Large Electric Systems
DC	–	Direct current
DGA	–	Dissolve Gas Analysis
ED	–	Effective deviation
FRA	–	Frequency Response Analysis
FDS	–	Frequency Domain Spectroscopy
HF	–	High frequency
HV	–	High voltage
IEC	–	International Electrotechnical Commission
IEEE	–	Institute of Electrical and Electronics Engineers
LF	–	Low frequency
LV	–	Low voltage
LVI	–	Low Voltage Impulse
MF	–	Medium frequency
MTM	–	Malaysia Transformer Manufacturing
NCEPRI	–	North China Electric Power Research Institute
NL	–	No load
OC	–	Open circuit
RMO-TW	–	Resistor Meter Ohmmeter – Transformer Winding
SC	–	Short circuit
TTR	–	Transformer turn ratio
TRF-100	–	Transformer Ratio Finder -100
TRM-203	–	Transformer Resistance Meter -203
UL	–	Under load
UWB	–	Ultra-wide band

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CHAPTER 1

INTRODUCTION

1.1 Research background

Power transformer is one of the most crucial equipment in an electrical power system. It is defined as a static electrical device used to transfer different level of voltage between different circuit connections through the concept of electromagnetic induction. Transformer is an important component in the power system which plays a key role to maintain the reliability and efficiency of electricity supply.

Monitoring and diagnosis of power transformers have been discussed significantly since in the last few decades. This topic has become an important issue since winding degradation which is highly related to insulation degradation is one of the most common faults in power transformers. Since operation of transformer has great impact on the stability of the power system network, it is important to prevent any damage that might lead to a consecutive electrical failure. It is important to distinguish and analyse winding damages to ensure the reliability and continuous power supply. Damage in transformer could consume Millions Ringgit in loss since it will be out of service for a long time, not to mention the cost to repair or replacement [1]. To monitor mechanical damage on transformers, Frequency Response Analysis (FRA) is well accepted in the industries as the best approach.

Although FRA test is widely employed and the equipment are now manufactured by many manufacturers, the interpretation of FRA signature is still a challenge and it requires skilled personnel to identify if any fault has occurred. This is due to at this stage, there is not enough references for FRA signature classification and quantification. Currently, there are four available standards or guidelines of FRA for testing the power transformer which are the Chinese Standard [2], CIGRE [3], IEC [4] and IEEE [5]. However, these documents only serve as guidelines for users to conduct the test. A comprehensive and reliable interpretation tools to assist users to evaluate a transformer mechanical status has yet to be established. Evaluating the frequency response of various winding configurations is the major area of interest within this field.

Many studies currently have been focusing toward establishing this tool to investigate various transformers fault. However, the FRA response is also greatly sensitive towards different factors including the arrangement of transformer windings. With the various possible arrangements of windings as shown in Figure 1.1, each arrangement possibly might produce a different frequency response.

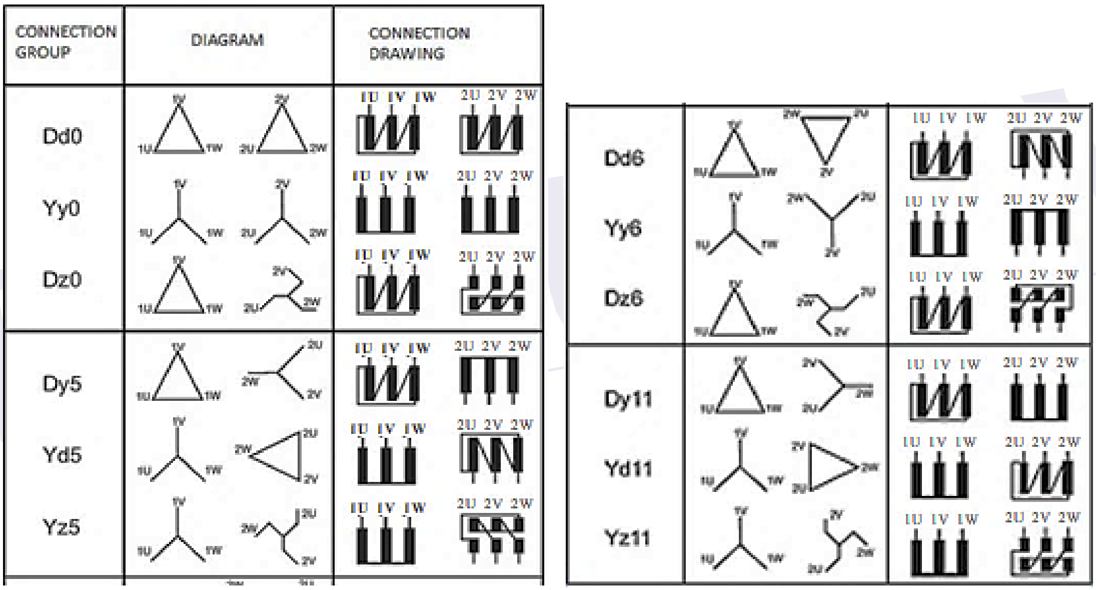

Figure 1.1: Various vector group which are expected to cause variations on the frequency response [6]

Besides that, a survey of faults in transformer by Hermann is illustrated in Figure 1.2. It shows that 49.4% of the total faults occur in the windings [7]. Most of the transformer faults are mainly occurred on the winding and has become a major concern to the manufacturers and asset owners. Therefore, more investigations on faulty winding is required. This is aimed to add up more information regarding interpretation of FRA response due to several types of faulty windings.

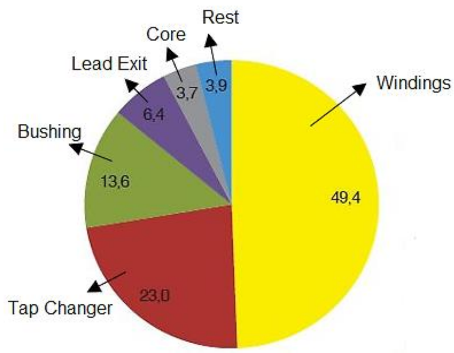

Figure 1.2: Fault location distribution of transformer failure survey [7]

Although faulty winding is the main interest in FRA, another circumstances that can give effect to the response should also be appraised. Without realizing that many aspects can influence the frequency response, one will immediately assume that the changes in the response is only due to the winding physical damage. In 2008, Secue and Mombello had reviewed the literature related to the application of FRA for diagnosing transformer condition in reference [8]. The review clarifies a number of factors that must be considered when implementing this method. For example, the frequency region and connection of non-tested terminals. Sofian *et al*. also presented a finding that shows the winding response of an autotransformer can be affected by the tertiary winding due to a coupling effect found in [9]. This indicates that a non-tested winding may also govern other winding responses. This is an important finding since it might cause misinterpretation and could cause catastrophic. Due to this, further studies need to be performed to establish if there is any probability to use FRA to clarify this condition assessment.

1.2 Problem Statement

Power transformer involve in high cost investment and an important equipment in power system network. For that reason, its conditions need to be monitored to ensure the appropriate level of reliability and an optimized operational life. Recently, more researchers have conveyed their concern in these issues due to utilities and power system operating under a rising cost-effecting pressure [10–12]. To examine the transformers, FRA is trusted by expert as one of the best testing methods. However, although the FRA method is widely employed and the instrumentation are greatly advanced, interpretation of FRA signatures is yet a challenge and it requires an expert to analyse them. This is due to at this stage, there is no proper guideline for FRA signature interpretation and elucidation.

Many studies currently have been focusing towards establishing this tool by investigating various winding deformations. However, frequency response of transformer is highly sensitive towards various factor and have been presented in various sources. For example, Wang *et al.*, has explained the effect of shunt impedance and length of measurement leads [10]. Kennedy *et al.*, on the other hand has described the effect of clamping structure [11]. Yousof has studied the effect of capacitance and mutual inductance between windings [12]. Also, towards non-mechanical factors like presented by Reykherdt and Davydov in [13]. It has presented the effect of oil as an insulation. Meanwhile, Yousof *et al*. has examined the influence of temperature and moisture content of insulation in transformer to the frequency response [14]. Besides all these factors that have been discussed, another factor which greatly influence the frequency response is the vector groups of winding, different types of faulty winding and the coupling effect in a three-phase transformer.

Windings in a three-phase transformer are arranged differently according to the requirement of the power station. Therefore, with the various possible arrangement of winding in as in Figure 1.1, it is expected to cause variation in the frequency response. On other hand, faulty winding due to short circuit fault is very detrimental. This matter has been investigated by Zhang *et al*. [15]. It is presented as a serious fault which has initiate various transformer breakdowns especially to three-phase transformers. In addition, Lawhead *et al.* has found that in a three-phase transformer, all phases are magnetically linked [6]. There is some coupling and power transfer between the phases, especially in the three-legged core design. The inter-phase coupling creates a mechanism where if a fault occurs on one phase, it will also generate current on the non-faulty phase windings. This vital yet fundamental understanding on response interpretation seems lacking in the literature. This is an important finding since it might cause misinterpretation and detrimental. Further investigation therefore is required to study the characteristics of response signatures due to these matters.

Therefore, several case studies are presented in this thesis. The first case is the sensitivity study towards the winding arrangements focusing on different vector groups. Since each winding arrangement is a different combination of electrical parameters, the response from 20 Hz to 2 MHz will be slightly or greatly different.

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